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Sustainable Trade and Supply Chains

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Sustainable Trade and Sustainable Supply Chains

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Executive Summary

A global transition toward sustainable trade and supply chains is essential in the age of climate change and energy decarbonization. Low-carbon technologies (LCTs) and the related minerals are at the forefront of this transition, playing a critical role in reducing greenhouse gas emissions and promoting sustainable development. The international trade of LCTs, including a wide range of products and technologies from renewable energy, energy-efficiency, energy storage and electric vehicles, is pivotal in accelerating the global adoption of climate friendly development, especially in the Global South. Considering the important role of China in the international LCT market, this report aims to provide a comprehensive analysis of LCT trade, focusing on countries' bilateral trade with China, its environmental impacts, and the economic factors shaping these trends.

As the demand for LCTs surges globally, countries are increasingly recognizing the economic opportunities of low carbon transition. These opportunities are particularly evident in the international trade, where policy support and international cooperation significantly influence the diffusion and adoption of these technologies. In particular, China emerged as a global leader in the production and export of LCTs, underscoring the shifting dynamics of the international LCT market. Over the past three decades, China has transitioned from a net importer to a net exporter of LCTs, driven by substantial investments in domestic clean technology manufacturing and supportive government policies. This transformation has not only bolstered China's position in the global market but also contributed significantly to the global supply of affordable and advanced LCTs. Understanding China's role and the factors driving its success provides valuable insights into the broader mechanisms of LCT trade.

China's increasing importance in international LCT trade have profound implications for both developed and developing countries. For developed countries, China's increasing market share has contributed to a more competitive and efficient market of LCTs and resulted in a significant shift in trade balances as developed countries have overtime become net importers. For developing countries, Chinese LCT products provide both environmental and technology opportunities. China's trade partners benefit from the increased availability of affordable LCTs, enabling them to progress toward sustainable development goals. These goals are achieved through both the direct environmental impact of LCTs and the potential diffusion of technology through trade. Therefore, it is important to identify key factors that shape countries' trade patterns with China, and to identify the climate implications of LCT imports from China.

In this article, we study the development of global LCT trade over the past three decades. Building on the literature in international trade, we identify and analyze key economic factors that shape countries' LCT trade with China. In the empirical section, we first present a detailed overview of global LCT trade trends from 1992 to 2022. We compile an original dataset using from reputable sources such as the International Monetary Fund (IMF) and the United Nations Statistical Division's Commodity Trade Statistics (Comtrade) database, we identify significant

shifts in export and import patterns, trade balances, and the evolving roles of high-income countries and emerging market and developing economies.

For statistical analysis, we employ gravity models to investigate the determinants of LCT and mineral trade with China and the impact of such trade on environmental outcomes. We find evidence of the importance of various factors such as economic development, trade openness, and exchange rate stability. Moreover, the analysis reveals the significant environmental benefits associated with LCT imports from China, particularly in reducing carbon emissions across different sectors. Human capital, political stability and foreign direct investment are found to be important channels that facilitate the adoption of LCTs obtained from China. Finally, we investigate the role of gender in LCT trade. We find that gender equality could contribute to countries' competitiveness in the global LCT supply chains. These findings contribute to the growing body of literature on sustainable trade and supply chains by providing an in-depth analysis of LCT trade dynamics and their environmental impacts.

Finally, based on the analysis, we put forward the following five policy recommendations:

Boost R&D subsidies for renewable energy to innovate and lead globally in energy security. China should maintain and potentially increase R&D subsidies for renewable energy technologies. This support should not be limited to promoting exports but also focus on enhancing domestic utilization and adoption of renewable energy solutions. By fostering innovation and technological advancements within the country, China can strengthen its position as a global leader in renewable energy while simultaneously addressing domestic energy needs and environmental challenges. Sustained R&D subsidies will drive innovation, making Chinese renewable energy technologies more competitive globally, reduce reliance on fossil fuels, lower carbon emissions, and improve energy security. Specifically, China can create a dedicated national fund to finance research and development projects in renewable energy, offer tax incentives to companies and research institutions that invest in renewable energy R&D, develop regional innovation hubs focused on renewable energy R&D to drive regional economic growth and specialization, and strengthen cooperation with Global South on policy banks and R&D in general.

Stabilize export prices to foster steady trade and investment relationships with partners. China should implement policies to maintain stable export prices, particularly with its major trading partners on low-carbon technology products and related minerals. Stable exports prices can reduce uncertainty for exporters, importers and investors, promoting steady trade and investment relationships. Specifically, China can monitor export prices for predictions and warnings, expand and enhance bilateral currency SWAP agreements with key trading partners, engage in regular macroeconomic policy coordination with key trading partners to promote export price stability.

Encourage outward FDI in renewable energy and low carbon technologies to promote global cooperation. China should continue to encourage and facilitate outward FDI of renewable energy and low carbon technologies to destination countries, especially those major trading partners. Outward FDI helps integrate China more deeply into the global economy, fostering stronger economic ties and collaboration. Firms can gain access to new markets, resources, and technologies, enhancing their productivity and competitiveness. Outward FDI can also diversify income sources and reduce economic vulnerability to domestic market fluctuations, especially for the renewable energy sector. Specifically, China can establish comprehensive financial incentives and support mechanisms to encourage Chinese enterprises to invest in renewable energy and low carbon technology sectors abroad, foster bilateral and multilateral partnerships to facilitate technology transfer and improve market access for Chinese renewable energy and low carbon technology firms, and pay particular attention to South-South cooperation.

Advance trade liberalization to foster sustainable trade practices and interconnected supply chains globally. China should pursue further trade liberalization for the development of sustainable trade and supply chains. Further trade liberalization can create more business opportunities for domestic firms in renewable energy sector and increase their productivity and competitiveness. Specifically, China can proceed diversification of export destinations, expansion of import scale, specialization of service trade, multi-layered regional economic cooperation and differentiation of the Belt and Road Initiative.

Improve external communication to eliminate misunderstandings about China's overcapacity. China's overcapacity is often misinterpreted, particularly in international contexts where it is wrongly linked to product dumping in developed countries like the United States. To effectively counter these misconceptions, China should enhance its external communication strategies. This includes ensuring consistency in messaging between domestic and international platforms, and articulating China's position clearly and confidently in global forums. Specifically, China should focus on the concept of overcapacity, the causes of overcapacity, the interpretation of industrial policy and the fallacies in the U.S. anti-dumping measures.

Key words： Sustainable Trade; Sustainable Supply Chains; low carbon technology; mineral trade

Contents

Sustainable Trade and Sustainable Supply Chains

1.1 Introduction

A global transition toward sustainable trade and supply chains is essential in the age of climate change and energy decarbonization. Low-carbon technologies (LCTs) and the related minerals are at the forefront of this transition, playing a critical role in reducing greenhouse gas emissions and promoting sustainable development. The international trade of LCTs, including a wide range of products and technologies from renewable energy, energy-efficiency, energy storage and electric vehicles, is pivotal in accelerating the global adoption of climate friendly development, especially in the Global South. Considering the important role of China in the international LCT market, this report aims to provide a comprehensive analysis of LCT trade, focusing on countries' bilateral trade with China, its environmental impacts, and the economic factors shaping these trends.

As the demand for LCTs surges globally, countries are increasingly recognizing the economic opportunities of low carbon transition. These opportunities are particularly evident in the international trade, where policy support and international cooperation significantly influence the diffusion and adoption of these technologies. In particular, China emerged as a global leader in the production and export of LCTs, underscoring the shifting dynamics of the international LCT market. Over the past three decades, China has transitioned from a net importer to a net exporter of LCTs, driven by substantial investments in domestic clean technology manufacturing and supportive government policies. This transformation has not only bolstered China's position in the global market but also contributed significantly to the global supply of affordable and advanced LCTs. Understanding China's role and the factors driving its success provides valuable insights into the broader mechanisms of LCT trade.

China's increasing importance in international LCT trade have profound implications for both developed and developing countries. For developed countries, China's increasing market share has contributed to a more competitive and efficient market of LCTs and resulted in a significant shift in trade balances as developed countries have overtime become net importers. For developing countries, Chinese LCT products provide both environmental and technology opportunities. China's trade partners benefit from the increased availability of affordable LCTs, enabling them to progress toward sustainable development goals. These goals are achieved through both the direct environmental impact of LCTs and the potential diffusion of technology through trade. Therefore, it is important to identify key factors that shape countries' trade patterns with China, and to identify the climate implications of LCT imports from China.

In this article, we study the development of global LCT trade over the past three decades. Building on the literature in international trade, we identify and analyze key economic factors that shape countries' LCT trade with China. In the empirical section, we first present a detailed overview of global LCT trade trends from 1992 to 2022. We compile an original dataset using from reputable sources such as the International Monetary Fund (IMF) and the United Nations Statistical Division's Commodity Trade Statistics (Comtrade) database, we identify significant shifts in export and import patterns, trade balances, and the evolving roles of high-income countries and emerging market and developing economies.

For statistical analysis, we employ gravity models to investigate the determinants of LCT and mineral trade with China and the impact of such trade on environmental outcomes. We find evidence on the importance of various factors such as economic development, trade openness, and exchange rate stability. Moreover, the analysis reveals the significant environmental benefits associated with LCT imports from China, particularly in reducing carbon emissions across different sectors. Human capital, political stability and foreign direct investment are found to be important channels that facilitate the adoption of LCTs obtained from China. These findings contribute to the growing body of literature on sustainable trade and supply chains by providing an in-depth analysis of LCT trade dynamics and their environmental impacts. We also find that gender equality in the labor force is positively associated with higher export of LCTs and transition minerals to China. This suggest that gender equality contributes significantly to countries's competitiveness in the global LCT trade and supply chains, and in reducing LCT trade deficits with China.

Finally, we provide policy recommendations based on the analysis. In particular, the authors advocate for sustained R&D investment in renewable energy technologies, the maintenance of stable export prices, encouragement of outward FDI, further trade liberalization and improve external communaction about overcapacity. These insights are valuable for policymakers, industry leaders, and researchers committed to advancing global sustainability and addressing the pressing challenges of climate change in China and beyond.

1.2Literature Review

1.2.1 Literature on low-carbon technology trade

Research on low-carbon technology trade involves aspects such as technology diffusion, policy support, and international cooperation. Porter and van der Linde (1995)[43] suggested that stringent environmental regulations could stimulate innovation and enhance the competitiveness of low-carbon technology products, known as the Porter hypothesis. Jaffe et al. (2005)[29] analyzed the impact of environmental policies on technological innovation and diffusion, finding that policy support is crucial for the promotion of low-carbon technologies. In recent years, Popp (2006)[42] and Johnstone et al. (2010)[30] have studied the international trade of renewable energy technologies, pointing out that policy incentives and international cooperation are the main drivers of low-carbon technology diffusion. Dechezleprêtre et al. (2011)[14] showed that multinational companies play an essential role in the research and promotion of low-carbon technologies.

China, among the world's most important producers and exporters of low-carbon technologies, has drawn scholarly attention. Zhang and Gallagher (2016)[56] found that China's policy support and market size are the main factors driving its low-carbon technology exports. Wang and Qin (2018)[53] analyzed the impact of the Belt and Road initiative on low-carbon technology trade, finding that the initiative has significantly promoted low-carbon technology cooperation between China and the countries along the route. Some studies have explored the promotion of low-carbon technologies within the Belt and Road initiative. Xie et al. (2021)[55] found that the Belt and Road initiative has significantly promoted low-carbon technology cooperation between China and the countries along the route. Zhang et al. (2019)[57] showed that China plays a crucial role in promoting the green Belt and Road construction by transferring technology and collaborating on projects, thereby enhancing the low-carbon technology levels of the countries along the route.

Importantly, three factors play a crucial role in the adoption of LCT through trade. First, human capital can influence the adoption and diffusion of low-carbon technologies, which in turn affects trade patterns. The development of human capital, through education and training, enhances the capacity of a country to innovate and utilize advanced technologies, including LCTs. Nelson and Phelps (1966)[39] argue that the stock of human capital in a country determines its ability to adopt new technologies. This theory underlines the importance of education and skill development in facilitating the adoption of LCTs and enhancing trade competitiveness. Second, political stability is a critical factor that influences the effectiveness of policies promoting low-carbon technologies and their subsequent impact on trade. Some studies show that political instability adversely affects economic growth by creating uncertainty, which deters investment and technological adoption (Alesina and Perotti, 1996)[1]. This finding suggests that stable political environments are conducive to the adoption of LCTs and the expansion of trade. Third, FDI is a significant channel for the transfer of low-carbon technologies and their integration into the global trade system. Harrison and Rodríguez-Clare (2010)[23] review the literature on trade and foreign direct investment, highlighting how FDI can enhance the technological capabilities of host countries. This improvement in technology, particularly in the realm of LCTs, leads to increased trade in low-carbon goods and services.

While there is substantial work on the role of policies and international cooperation in LCT trade, there is less theoretical development on the integration of low-carbon technology trade with broader economic and environmental models. In addition, empirical studies lack comprehensive data linking LCT trade with specific environmental outcomes. There is also a shortage of empirical studies focusing on the role of emerging economies in the global LCT market. For instance, studies by Wang and Qin (2018)[53] and Xie et al. (2021)[55] highlight the impact of the Belt and Road Initiative on LCT trade but suggest that more detailed analyses are needed to understand the full scope of these dynamics. This study contributes to the literature on three grounds: First, by exploring trends in LCT trade over the past decades and identifying determinants of LCT trade with China, the study enhances the empirical understanding of factors driving LCT trade. It builds on previous works by Popp (2006)[42] and Johnstone et al. (2010)[30], who identified policy incentives and international cooperation as key drivers of LCT diffusion. Second, the empirical analysis on the effects of LCT imports from China on economic growth and environmental outcomes provides valuable insights into the direct and indirect impacts of LCT trade. This helps in understanding the broader implications of LCT trade on sustainable development. The findings of mechanisms support and extend the conclusions of studies like those by Levinson and Taylor (2008)[34] and Kellenberg (2009)[32], which examine the relationship between trade, environmental regulation, and pollution haven effects. Third, the study highlights the significant role of emerging economies in the global LCT market. This addresses the empirical gap related to the participation of developing countries in LCT trade, as discussed by Zhang and Gallagher (2016)[56].

1.2.2 Literature on the impact of trade on environment

A strand of literature investigates the direct impact of trade on the environment. Low and Yeats (1992)[36] and Tobey (1990)[51] studied the impact of international environmental agreements on trade flows, finding that such agreements can promote the international diffusion of clean technologies. Furthermore, Antweiler et al. (2001)[4] suggested that trade affects environmental quality through scale effects, composition effects, and technique effects. Copeland and Taylor (2004)[12] further explored the specific impacts of trade liberalization on the environment, arguing that trade can improve the environment through technological diffusion and income effects but may also exacerbate pollution. Cole and Elliott (2003)[11] empirically found that some developing countries have indeed attracted a significant number of pollution-intensive industries. Levinson and Taylor (2008)[34] further validated this hypothesis, indicating that differences in environmental regulations significantly influence industry relocation and trade patterns. Kellenberg (2009)[32] showed that countries with strict environmental regulations can gain a competitive advantage in the global market through technological innovation and industrial upgrading. Zhou et al. (2017)[58] explored the environmental impact of trade between

China and other countries, finding that China's environmental policies have gradually improved the negative environmental effects of trade. Increasing research has also focused on the specific impact of trade openness on the environment. For example, Wang et al. (2020)[52] found that trade openness can reduce carbon emissions by promoting technological progress and industrial upgrading. Hertwich and Peters (2009)[25] pointed out the contribution of global supply chains to the carbon footprint, emphasizing the role of international trade in carbon emissions.

There are also studies discussing the indirect impact on the environment through economic growth. Grossman and Krueger (1991)[22] proposed the "Environmental Kuznets Curve", which hypothesizes that environmental pollution increases in the early stages of economic growth but decreases after reaching a certain level. Studies by Stern (2004)[47] and Dinda (2004)[16] support this hypothesis, suggesting that technological progress and increased environmental awareness due to economic growth can mitigate pollution. Taguchi (2013)[49] examined the applicability of the Environmental Kuznets Curve in different countries, finding that pollution levels in middle-income countries gradually decrease. While we note that this work was limited to a small set of pollutants and didn't find correlation between per capita income and greenhouse gas emissions.

1.2.3 Literature on gravity models

The gravity model has been an important tool in international trade research, with a wide range of applications and developments. Tinbergen (1962)[50] and Pöyhönen (1963)[44] were the first to apply the gravity model to trade research, finding that trade volume between countries is directly proportional to their economic size and inversely proportional to their geographical distance. Subsequently, the model was widely applied and augmented. Linnemann (1966)[35] extended the model by considering factors such as population and economic cooperation. Anderson (1979)[2] proposed the multi-commodity framework, improving the traditional gravity model to make it more explanatory. Bergstrand (1985)[10] enriched the application of the gravity model by introducing non-tariff barriers and monetary factors. Deardorff (1998)[13] suggested that the gravity model not only applies to the prediction of trade flows but also explains trade patterns and policy impacts.

Over time, the application of the gravity model has expanded to different research fields. Eichengreen and Irwin (1995)[19] studied the impact of historical trade policies on trade flows. Rose (2000)[45] empirically analyzed the relationship between bilateral investment treaties and trade flows. In recent years, scholars such as Egger (2002)[18] and Baier and Bergstrand (2007)[7] have used gravity models to study the effects of regional trade agreements, finding that these agreements significantly promote trade flows among member countries. Fally (2015)[20] used gravity models to analyze trade flows within global value chains, highlighting the increasing impact of globalization on trade flows.

In addition, some studies discussed the theory and estimation of this model. Head and Mayer (2014)[24] reviewed the developments in gravity models, emphasizing their theoretical foundations and empirical applications. Anderson and Yotov (2020)[3] proposed more precise estimation methods by studying multiple variables within gravity models. Santos Silva and Tenreyro (2006)[46] introduced the PPML method, effectively addressing heteroskedasticity issues in gravity models.

1.3 Data

To identify trade in Low Carbon Technology (LCT) Goods we rely on a classification published by the IMF in the report Data for a Greener World: A Guide for Practitioners and Policymakers (Arslanalp, Kost and

Quirós-Romero 2023)[6]. The list comprises 124 six-digit product codes classified according to the Harmonized System (HS) nomenclature. The Harmonized System is a standard international nomenclature used by customs authorities for the purpose of tariff calculations. The United Nations Statistical Division's Commodity Trade Statistics (Comtrade) database records bilateral trade transactions for customs and tariff purposes and is the primary source of data for this study. This data is open access and is the most used trade data source. The period of analysis of this study is from 1992 to 2022, as trade data for China is only available starting in 1992. The main country groups included in the analysis are Higher-Income economies, Emerging Markets and Developing Economies (EMDEs) excluding China, and China as defined by the World Economic Outlook classification. Additionally, the study uses the World Bank's list of transition minerals presented in the Minerals for Climate Action report as the main source of classification of transition minerals to analyze trends in international trade in transition minerals. Trade data relating to the thirteen transition minerals is also from the Comtrade database.

The IMF list of LCT products combines prior lists of low-carbon products published by four main sources. The majority of the products (54) appear in the Asia-Pacific Economic Cooperation (APEC) List of Environmental Goods (APEC 2012; Kuriyama 2021)[33]. APEC produced this list in 2012 as part of their effort to promote trade by committing to reduce tariffs on the products identified by 2015. The World Bank 's 2008 publication International Trade and Climate Change: Economic, Legal and Institutional Perspectives, also calls for the liberalization of trade in the forty-three products identified (World Bank 2008). The third source is Glachant, Dussaux, and Dechezleprêtre, who authored numerous academic publications focused on the diffusion of LCTs and identified thirty products that are climate-change-related technologies. There is some overlap between these three sources. Therefore, in a World Bank publication, Technology Transfer and Innovation for Low-Carbon Development, Pigato et al. (2020)[41] combine these three lists to produce a comprehensive list of 107 LCTs. Finally, the IMF list of Low Carbon Technology Goods used in this study includes 17 additional products mainly relating to electric vehicles and battery components such as lithium.

The IMF list facilitates the analysis of trends in total bilateral LCT trade. However, since the list does not offer a grouping of individual LCT products by the type of industry or sector, the current list does not facilitate a sector-wise analysis. Such an analysis is crucial in systematically assessing the LCT supply chain between higher-income and emerging market economies. Therefore, this study's primary innovation is developing a classification system that aggregates the 124 products of the IMF list into broader categories depending on the LCT sector and the type of technology it deploys. For each product on the IMF list, we assign a sector from either buildings, energy storage, pollution control, power generation, consumer appliance, transportation, or environmental monitoring. Additionally, we assign a corresponding technology class for each product. For example, the technology class for power generation includes bio-energy, geothermal, hydroelectric, nuclear, solar, wind, solar, and renewable energy modular parts.

We used existing descriptions from the data sources mentioned above to create these aggregate sector types and assign the corresponding technology class. The APEC List of Environmental Goods and the World Bank lists offer a detailed description of each product's function as an LCT. We used these descriptions to determine the technology class of each product. Additionally, the accompanying analytical study of the APEC list and work by Glachant, Dussaux, and Dechezleprêtre use some aggregate categories to describe their data. We combined these existing categories and included new categories, such as transportation, to categorize electric and hybrid vehicles. Table 1 shows the finalized categorization.

Table 1 Low Carbon Technology Classification

No	Sector	Technology Class
1	***Buildings***	Heating /cooling Insulation Lighting Other
2	***Energy Storage***	Batteries
3	***Pollution Control***	Air Solid-waste Water
4	***Power Generation***	Bio-energy Geothermal Hydroelectric Nuclear Solar Wind RE modular parts
5	***Consumer Appliance***	Energy-efficient
6	***Transport***	EV Hybrid Other
7	***Environmental Monitoring***	Air Other Water

Most of the products (30) fall under power generation and contribute to large trade volumes, as described in the next section. The products are evenly distributed among the technology classes (bio-energy, geothermal, hydroelectric, nuclear, solar, wind, solar, and renewable energy modular parts) within the section. Buildings, energy storage, pollution control, consumer appliances, transport, and environmental monitoring comprise 20,13, 24, 10, 9, and 17 products, respectively, and in all cases, they are mostly evenly distributed among the technology classes. It is also important to note that this LCT goods list does not include transition minerals besides lithium. In the case of lithium, it is included in both the LCTs and transition minerals lists, as well as the trade data analysis pertaining to each list.

The main limitation of the dataset is that the IMF list may not be an exhaustive list of the inputs and products that can be classified as low-carbon technologies. For example, along with lithium-ion batteries (included in the list), hydrogen fuel cells, and flywheel systems are components of Energy Storage Systems (ESS) for improving energy efficiency. However, the IMF list does not include the latter two products. Another example is the exclusion of basic components such as reciprocating engines and microturbines used in Combined Heat and Power (CHP) Technologies, which is a common type of energy-saving LCT. Therefore, this study does not capture all trade in LCTs. However, it is the most comprehensive list available as of now. Future work should focus on fine-tuning this list to include all relevant products that are inputs to the production of LCTs. Another weakness of the dataset is the possibility of overestimating traded values of LCTs. For example, sections such as environmental monitoring include multipurpose measuring equipment such as spectrometers, chromatographs, and surveying equipment. We know that not all of this equipment will be used for environmental monitoring, if at all. A similar case is renewable energy (RE) modular parts of the power generation section. Products under this category include electric generators, transformers, and boards and panels for electricity distribution; similar to the equipment under environmental monitoring, not all of these products will be utilized for renewable energy generation. This issue is unavoidable as tracking product use information at the country level is impossible.

1.4An Overview of Global Low Carbon Technology Trade

The global trade in LTCs is increasingly pivotal for the world's transition toward carbon neutrality. Drawing from the new dataset described in the previous section, this section provides an overview of the significant trends in the LCT trade over the past 30 years, highlighting the evolution of market dynamics and the central role played by key nations, notably China. As 2030 approaches with limited action on climate change, understanding these trends becomes crucial for policymakers, industry leaders, and researchers focused on fostering a resilient global low-carbon economy.

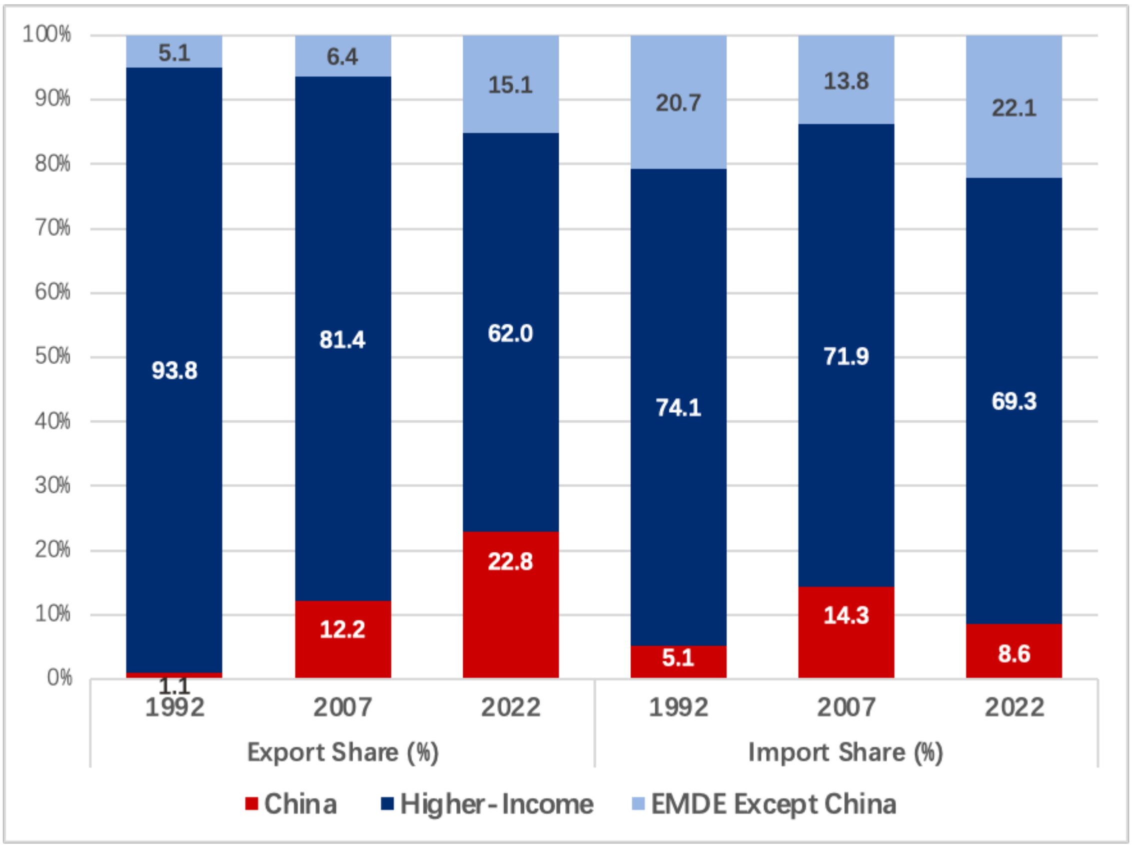

Figure 1 World Low Carbon Technology Trade (percentage share)

Like the global economy, the structure of world trade of LCTs changed dramatically over the past three decades. Figure 1 illustrates the share of imports and exports in China, high-income countries, and Emerging Market and Developing Economies (EMDE) within the global LCT trade for the years 1992, 2007, and 2022.

Specifically, high-income countries, which have traditionally dominated the export market, saw their share decrease from 93.8% in 1992 to 81.4% in 2007, and further to 62% in 2022. In contrast, developing countries, particularly China, have expanded their presence in the export market significantly. China's export share has seen a steady rise from 1.1% in 1992 to 12.2% in 2007. Post-2007, China's LCT exports have tripled compared to the growth in the previous 15 years, reaching 22.8% of the global total by 2022. During the same period, exports from other EMDEs, excluding China, have also more than doubled, increasing from 6.4% to 15.1% of the world's total exports (Bandara et al. forthcoming)[9].

In the import market, high-income countries have consistently been the main importers of LCTs throughout the past three decades. Their import share has only slightly decreased, moving from 74.1% in 1992 to 71.9% in 2007, and further to 69.3% in 2022. This large share suggests that while high-income countries continue to lead in LCT imports, there is a gradual diversification in global LCT import dynamics. In the global South, China's share in the LCT import market initially increased, rising from 5.1% in 1992 to 14.3% in 2007. However, this trend reversed in the following years, and China's import share dropping to 8.6% by 2022. This decline is largely attributable to the development of its domestic LCT industry, reducing reliance on imports as local production capacities and technologies improved.

Conversely, the import share of other EMDEs changed in the opposite direction. After a decline from 1992 to 2007 of about 7%, their import share significantly rebounded, surpassing the 1992 level to reach 22.1% by 2022. This increase suggests a growing engagement and investment in LCTs among these economies, potentially driven by increasing environmental awareness, international climate commitments, and the declining cost of LCTs making them more accessible.

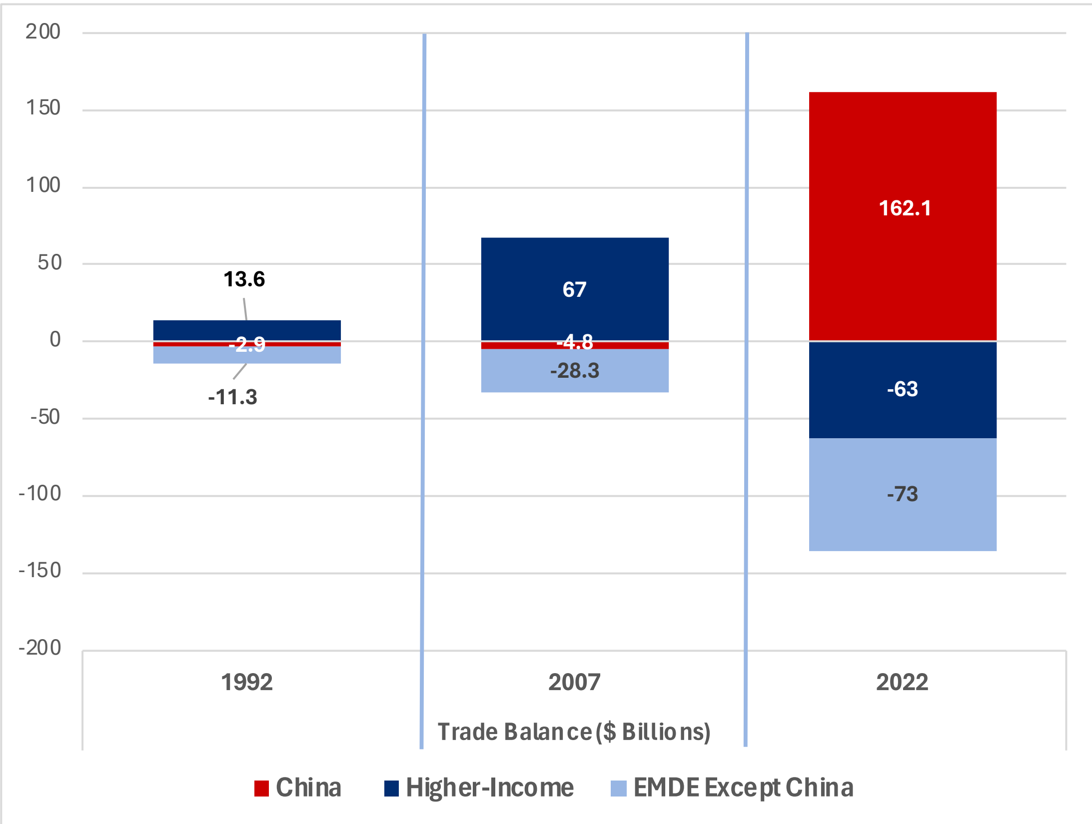

Figure 2 World Low Carbon Technology Trade Balance (Billion USD)

These developments in the import-export market have significantly influenced LCTs' trade balance. Figure

2 provides a clear depiction of the trade balance, measured in billions of USD (LCT exports minus imports), across three different groups. As shown in the figure, China emerges as the primary beneficiary of structural changes in the global LCT market. Historically, China was a net importer of LCT products up until the late 2000s. However, post-2008, due to the cultivation of a robust clean technology manufacturing supported by strong government industrial policies, China transitioned to a net exporter (Huang et al. 2016; Nemet 2019)[2640]. This shift enabled China to supply the global market with cost-effective LCT products. By 2022, China's net export of LCTs soared to $162.1 billion, establishing its dominance in the global market.

In contrast, high-income countries, which were collectively net exporters of LCTs until the late 2000s, experienced a reversal in global trade. As China's clean technology industry expanded, these countries transitioned to net importers. The combined trade balance of these nations shifted from a positive $67 billion to a deficit of $63 billion by 2022. This shift reflects the changing dynamics where high-income countries increasingly rely on imports to meet their growing LCT demands, partly due to competitive pricing and advanced technology from China. For the group of developing countries, the trade deficit has worsened over the years. Despite this growing deficit, the broader implications suggest a complex interplay of factors. These economies are likely experiencing increased trade deficit of LCTs due to insufficient domestic production capacity and the urgent need to meet environmental targets. However, this also indicates a dependency that could stifle local industry development unless balanced with supportive policies to build domestic LCT sectors.

China's increase in exports post-2007 correlates with substantial investments in its domestic LCT industry (Zeng et al. 2014, Nemet 2019, Jackson et al. 2021)[4028]. This boost can be attributed to improved access to technology, both international and domestic support for climate and environmental actions, and enhanced local capacities to implement pro-LCT industrial policies. As China strengthens its manufacturing capabilities in sectors such as renewable energy technologies, electric vehicles, and energy efficiency, its reliance on imports has diminished. Affordable Chinese LCT products have penetrated the global market. This shift not only supports China's energy security and economic strategy but also positions it as a potential future exporter rather than a net importer of LCTs.

In addition, the rise in imports among other EMDEs (except China) underscores a broader trend where these regions are catching up in low-carbon deployment. This increase reflects an expanding engagement with global low-carbon initiatives and indicates a growing capacity and demand within these economies for sustainable technologies. This shift is pivotal as it highlights the dynamic nature of the global LCT market, where economic development, technological advancement, and policy frameworks interact to reshape the landscape of international trade in these crucial technologies. However, the domestic LCT industry in non-these EMDEs has lagged behind the expansion of the LCT markets, leading to substantial trade deficits, largely their market to imports from China. These countries often represent a small fraction of global trade but experienced significant trade imbalances. This situation is concerning given the trajectory of future emissions in these regions, but it also presents an opportunity for South-South cooperation, especially with China. Such collaboration should foster the development of local industries, facilitate local LCT innovation, reduce dependency on imports, and enhance regional capacities to meet the growing demand for low-carbon technologies.

Overall, the data suggests a significant reorientation in the global LCT trade from advanced economies to the Global South. High-income countries, while still holding a major portion of the market, are the losing export market to EMDEs, especially China. As China and other EMDEs continue to enhance their capabilities and increase their market shares, they could potentially diversify the global LCT production and accelerate global energy transitions.

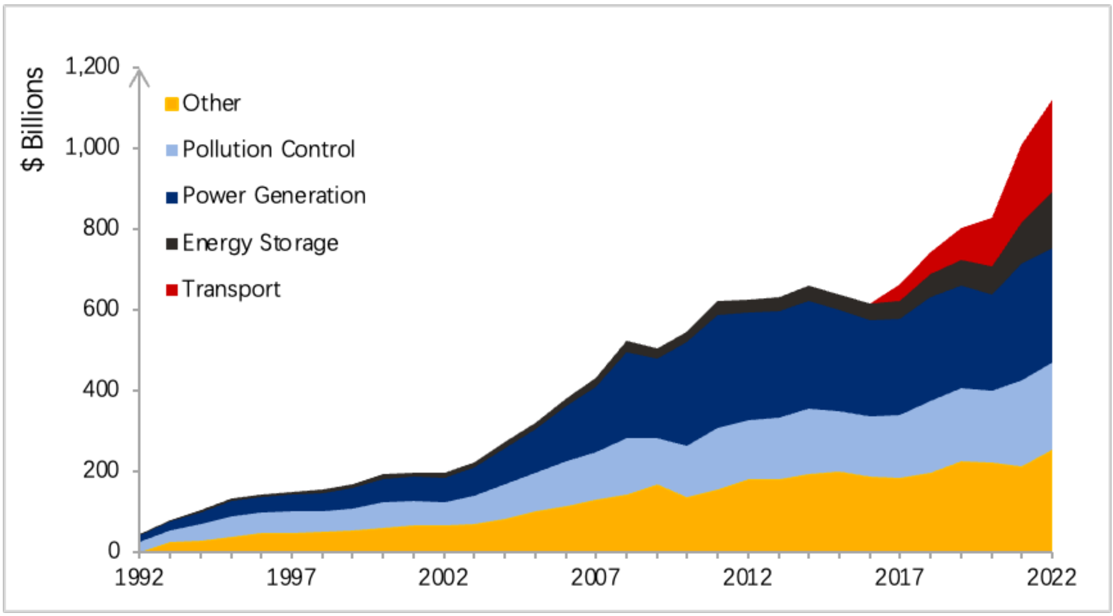

Figure 3 Total World Exports in Low Carbon Technologies

The structural change in trade balance not only highlights the changing landscape of global manufacturing, but also reflects the development and investments in different LCTs sectors. Figure 3 provides a detailed breakdown of LCT exports by sector, illustrating substantial expansion and change in the landscape of global demand for various LCTs over time. In general, the total value of export market grows from $71 billion in 1992 to $1,119 billion in 2022. The clean power generation technologies, mainly consisting of solar and wind, outstripped all other sectors in the early 2000s and continued to expand to $281 million in 2022.

Another major development in global LCT export occurred in 2017 with the explosive growth in the clean transportation sector, and in particular, electric vehicles. The export of clean transportation surged dramatically, marking a significant change in the composition of the LCT trade. Its share of the total LCT export vaulted from a mere 0.02% in 2016 to 5.9% in 2017, and subsequently raised to over 20% in 2022. This surge reflects broader trends in global priorities and innovations, particularly the rapid adoption and development of electric vehicles and other sustainable transport solutions, which is consistent with global efforts to tackle urban pollution and climate change. The growth not only underscores major climate actions, but also highlights EV and energy storage technologies have matured and developed into a large component of the overall LCT market (Jones et al. 2020, Sun et al. 2022, IEA 2023)[314827].

These trends in the global LCT export market indicate the building blocks of a clear and sustained push for decarbonization. The resilience of this market, evident from its recovery post-2008 and its ability to overcome various trade barriers since 2012, signals a stable commitment worldwide to transition towards more sustainable energy and transportation systems. This sector's growth is likely to continue as technological advancements are made and as policies further incentivizing low-carbon technologies are implemented globally.

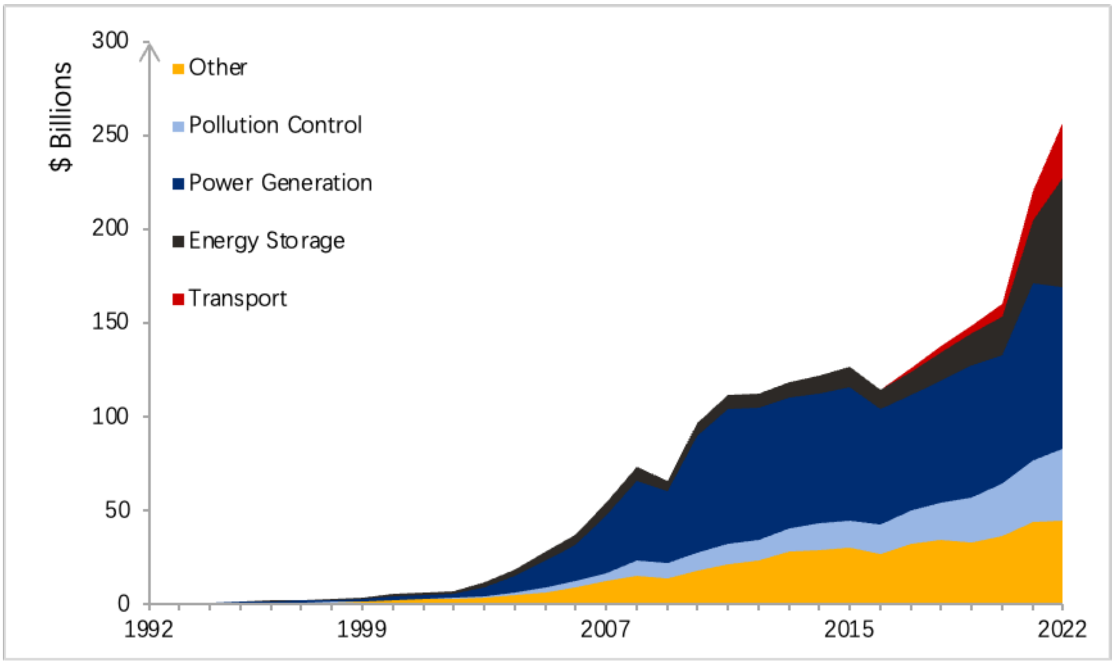

Figure 4 Total Chinese Exports in LCTs by Sector

China's LCT exports is consistent with global trends, but with its own unique characteristics, as shown in Figure 4. The country has focused significantly on advanced technologies for decarbonization, such as clean technologies for power generation (especially wind and solar), energy storage, and transportation, which collectively drive the bulk of its LCT exports.

Since 2004, China's exports of clean power generation have seen substantial growth, reaching over $14 billion or 14% of the global total export. However, during the 2010s, this sector experienced stagnation and fluctuations in export volumes—ranging from $60 billion to $71 billion—largely due to anti-dumping tariffs imposed by the United States and Europe on Chinese solar products. Despite these challenges, the export value grew to $94 billion in 2021, marking a 37% increase from the pre-Pandemic era, and has since maintained over 30% of the global total. These figures underscore China's pivotal role in the global LCT market, especially in sectors where it has managed to overcome significant trade barriers and maintain a competitive edge.

Other advanced clean technology products from China are becoming increasingly competitive in the global market. In 2001, China's energy storage exports have reached $1 billion, and while this number may seem relatively small in absolute terms, it represents 11% of the global share, giving China a competitive edge in the energy storage market. Over the next two decades, China's exports of energy storage products continued to grow robustly, reaching $10 billion in 2015 and doubling to $20 billion in 2020. During the post-pandemic era, the market share of Chinese products expanded significantly, reaching $58 billion in 2022, which accounts for over 30% of the global total. Similarly, China's market share in global clean transportation technologies mirrored this growth pattern, indicating a strategic alignment with global demand trends in critical sectors of the low-carbon economy. China's export of low-carbon transportation products experienced a significant growth in 2017, driving the global expansion of the EV industry. From having almost zero in the global clean transport export market before 2016, China's share rose dramatically to 5% in 2017. By 2022, this figure had escalated to $29 billion, representing 13% of the global total.

In 2022, the combination of clean power generation, energy storage, and transportation products accounted for $174 billion, or 68% of total Chinese LCT exports. This pattern highlights China's strategic focus on scaling up its capabilities in the advanced clean technologies, an area critical for the global energy transition. The substantial increase in market share, particularly in the years following the Pandemic, underlines technological achievements and resilience against market barriers within China's clean energy industry, positioning it as a leading player in the global market.

Table 2 Share of Total Chinese Exports in LCTs by Trading Partner Income and Region

Income Group	1992	2007	2022
High income	63.8	79.6	70.1
Upper middle income	13.7	0.5	15.9
Lower middle income	21.5	7.0	13.6
Low income	1.0	12.9	0.5

Region	1992	2007	2022
East Asia & Pacific	61.4	50.9	30.8
Europe & Central Asia	10	24.4	37
Latin America & Caribbean	0.8	4.4	6.9
Middle East & North Africa	4.4	2.3	4.7
North America	6.7	13.2	13.1
South Asia	16.1	3.5	5.3
Sub-Saharan Africa	0.6	1.3	2.2

In terms of destination, the main consumer of Chinese LCT products are high-income countries. Table 2 illustrates the regional distribution of Chinese LCT exports, highlighting a significant preference for high-income countries, which account for over 70% of total exports. Notably, exports to Europe have shown substantial growth, increasing from 10% in 1992 to 24.4% in 2007, and further to 37% in 2022. In contrast, exports to North America have remained relatively stable over the years. Combined, exports to Europe and North America constitute about 43% of total Chinese LCT exports.

Other income groups are also seeing growth in imports of Chinese LCTs. Exports to upper-middle and lower-middle-income countries represent 15.9% and 13.6%, respectively. However, the share of exports to low-income countries, while significant in the 2000s, has declined in subsequent years, accounting for just 0.5% of Chinese exports in 2022. This trend is mirrored in the regional data, with Sub-Saharan Africa purchasing only 2.2% of China's exports in 2022. Interestingly, the export share of Chinese LCTs to the East Asia and Pacific region has seen a significant decline, dropping from over 50% before 2007 to just 30% in 2022. These changes in export market underscores developments in LCT demand, suggesting an export orientation towards countries with more progressive climate policy, particularly in Europe and North America, where investment for LCTs continues to grow. Meanwhile, the relatively low figures for low-income regions suggest potential limited market demand, possibly due to affordability issues or lack of infrastructure to support the adoption of LCTs.

1.5Empirical Design

1.5.1 The determinants of LCT trade with China

After creating the LCT Goods dataset, we next carry out the empirical analysis of China's trade in LCT goods within the gravity-equation framework. The development of gravity models has been discussed in the previous section of literature. To construct outcome and control variables, we obtain country-level time-variant variables mainly from the World Development Indicators (WDI) dataset. All the explanatory variables are standardized as z-scores before used in the regressions. However, we present the summary statistics for all the variables in their original values, as in the following table.

Table 3 Summary Statistics (Original Values)

Variables	(1) N	(2) Mean	(3) Sd	(4) Min	(5) Max
LCT exports to China (1000$)	2,964	419,596.861	2291309.087	0.001	29231552.000
LCT imports from China (1000$)	4,697	260,305.829	1095671.068	0.024	19581512.000
Minerals exports to China (1000$)	2,164	797,745.334	4432737.489	0.007	78880472.000
Minerals imports from China (1000$)	1,941	9,474.610	66,353.792	0.001	1559630.000
Compulsory education	3,447	9.305	2.212	4.000	16.000
Control of corruption	3,640	-0.058	1.001	-1.849	2.459
Domestic credit (% of GDP)	3,666	48.904	51.091	0.002	525.704
FDI inflows (% of GDP)	4,554	4.935	15.212	-57.532	449.081
GDP growth	4,569	3.661	5.697	-50.339	149.973
Gross domestic savings (% of GDP)	4,091	19.596	16.948	-86.912	87.827
Inflation	4,266	14.789	131.869	-16.860	4,734.914
Foreign aid received per capita	3,487	99.975	266.329	-131.942	4,732.423
Political stability	3,655	-0.067	0.979	-3.313	1.759
Population growth	4,697	1.505	1.604	-16.049	19.360
Real interest rate	2,903	6.578	12.519	-93.513	139.964
Regulatory quality	3,631	-0.061	0.982	-2.548	2.255
Weighted mean tariff	3,206	7.077	10.332	0.000	421.500
GDP per capital (ln)	4,480	9.159	1.189	6.079	11.701
Total reserves (% of GDP)	4,183	16.882	17.400	0.029	229.480
REER index (rolling SD)	2,288	5.387	7.449	0.143	110.278
Inflation (rolling SD)	4,047	11.673	104.557	0.080	3,655.932
Trade openness	4,107	0.597	0.347	0.092	3.445
GDP (ln)	4,619	23.851	2.354	17.150	30.694
CO2 emissions (kt) (ln)	4,697	9.357	2.413	1.887	15.569
CO2 emissions (tons per capita)	4,697	4.372	5.643	0.022	47.657
CO2 emissions (kg per PPP GDP)	4,528	0.290	0.257	0.034	2.382
CO2 emissions (kg per 2017 PPP GDP)	4,490	0.240	0.202	0.022	2.085

As suggested in the previous analysis, trade in LCT products has been increasing substantially over the past years between China and China's trade partners. However, such growth is heterogeneous across different groups of countries. Therefore, in this part of the analysis, we explore the potential determinants of LCT trade with China for China's trade partners. In other words, we estimate the following regression model:

$$\mathrm{LCT}_{i,t} = \alpha + \beta X_{i,t-1} + \phi_i + \eta_t + \varepsilon_{i,t} \quad (1)$$

where, $\mathrm{LCT}_{i,t}$ is China's total exports/imports of LCT to/from trade partner i in year t; $X_{i,t-1}$ includes all the variables that could affect the LCT trade with China in trade partner i in year t-1, which is one-period lagged. The choice of the explanatory variables follows the literature in gravity equation; ϕ_i is trade partner fixed effects; η_t is year fixed effects.

1.5.2 The determinants of mineral trade with China

As transition minerals play an important role in the supply chains of low carbon technology, we further explore the potential determinants of trade in transition minerals with China for China's trade partners. We establish the following regression model:

$$\mathrm{Minerals}_{i,t} = \alpha + \beta X_{i,t-1} + \phi_i + \eta_t + \varepsilon_{i,t} \quad (2)$$

where, $\mathrm{Minerals}_{i,t}$ is China's total exports/imports of transition minerals to/from trade partner i in year t; $X_{i,t-1}$ includes all the variables that could affect the mineral trade with China in trade partner i in year t-1, which is one-period lagged; The choice of the explanatory variables again follows the literature in gravity equation; ϕ_i is trade partner fixed effects; η_t is year fixed effects.

1.5.3 The environmental effects of LCT imports from China

In this part of our analysis, we consider LCT imports from China as the independent variable of interest. We examine the impact of LCT trade with China on a country's environmental performance. Those variables include CO2, NO, and methane emissions in total and in industry level. The potential environmental effects of LCT imports could exist through both a direct channel such as the adoption of newer LCT technology and an indirect channel such as learning by trading.

We expect that LCT imports from China would reduce a country's carbon emissions, measured in terms of absolute emissions levels, per capita and emissions per GDP. And we also expect that the impact would be heterogeneous across sectors. For instance, importing China's electronic vehicles to replace fossil fuel vehicles may reduce trade partners' carbon emissions in the transportation sector.

In addition to the key variable of interest, we consider a set of control variables, which include GDP growth, log-transformed GDP size and GDP per capita, gross domestic savings, domestic credit provided by financial sector, inflation and the rolling standard deviation of inflation, real interest rate, the rolling standard deviation of real effective exchange rate, total reserves, openness index, population growth, among others. All the variables are obtained from the WDI dataset as remarked before.

Specifically, to estimate the impact of China's exports and imports of low carbon technology goods on a country's economic and environmental performance, we construct the following regression model:

$$Y_{i,t} = \alpha + \beta \mathrm{LCT}_{i,t-1} + \Gamma' X_{i,t-1} + \phi_i + \eta_t + \varepsilon_{i,t} \quad (3)$$

where $Y_{i,t}$ is environmental outcome variable in trade partner i in year t; $\mathrm{LCT}_{i,t-1}$ is China's total exports of LCT to trade partner i in year t-1, which is one-period lagged given the time needed for LCT adoption; $X_{i,t-1}$ includes all the control variables in trade partner i in year t-1, which is also one-period lagged; ϕ_i is trade partner fixed effects; η_t is year fixed effects.

1.5.4 Economic mechanisms

The baseline regressions illustrate the overall effects of LCT imports from China on a country's environmental variables. Next, we examine the mechanisms through which the above effects take place. The regression model is as following:

$$Y_{i,t} = \alpha + \beta_1 \mathrm{LCT}_{i,t-1} \times \mathrm{CV}_{i,t-1} + \beta_2 \mathrm{LCT}_{i,t-1} + \beta_3 \mathrm{CV}_{i,t-1} + \Gamma' X_{i,t-1} + \phi_i + \eta_t + \varepsilon_{i,t} \quad (4)$$

where the notations are the same as Equation (3), except the newly included variable $CV_{i,t-1}$. $CV_{i,t-1}$ denotes the channel variable in trade partner i in year t-1. The effect of $LCT_{i,t-1}$ on the outcome variable can be affected by the value of $CV_{i,t-1}$ through the interaction term $LCT_{i,t-1} \times CV_{i,t-1}$. According to the relevant theories in economic growth and trade as discussed in the literature review, we consider the following variables as potential channels: Human capital, political stability, foreign direct investment inflows, as well as foreign aid received. Finally, although we have lagged all the right-hand-side variables to avoid reverse causality, we recognize that the empirical design delivered in the current section may still have endogeneity problem. We plan to further address the issue in our research in the future.

1.6Empirical Findings

1.6.1 The determinants of LCT trade with China

We present the results for the determinants of LCT trade with China in Table 4. Column (1) refers to LCT imports from China; column (2) refers to LCT exports to China. First, economic size proxied by GDP scale suggests that countries with higher GDP tend to import more LCT products from China, which is consistent with the data and the predictions from gravity model. While, economic development level proxied by GDP per capita tends to have opposite effects on LCT imports and exports: all other things being equal, countries with higher GDP per capital import relatively less LCT products from China, while export more LCT products to China. Second, inflation and the uncertainty about the inflation (proxied by the 4-year rolling standard deviation) are negatively correlated with LCT trade with China, either imports or exports. Meanwhile, it is surprising to observe a positive correlation between the 4-year rolling standard deviation of real effective exchange rate and LCT trade with China. Finally, trade openness and political stability both stimulate LCT imports from China, while tariff seems to play a less important role in LCT trade with China.

Table 4 Determinants of LCT Trade with China

	LCT imports from China (ln)	LCT exports to China (ln)
	(1)	(2)
GDP	4.081***	-2.179
	(7.87)	(-1.43)
GDP growth	0.051	-0.201
	(0.98)	(-1.44)
GDP per capita	-2.007***	4.993***
	(-4.28)	(3.50)
Gross domestic savings	0.118	0.406
	(1.25)	(1.56)
Domestic credit	-0.041	-0.037
	(-0.68)	(-0.26)
Inflation	-2.766*	-14.001***
	(-1.78)	(-3.46)
Inflation (rolling SD)	0.052	-2.149***
	(0.19)	(-3.30)
Real interest rate	0.062	0.179
	(1.45)	(1.45)
REER index (rolling SD)	0.111**	0.494***
	(2.11)	(3.51)
Total reserves	-0.352***	0.005
	(-3.42)	(0.02)
Trade openness	0.411***	0.147
	(6.10)	(0.87)
Population growth	0.021	-0.030
	(0.29)	(-0.16)
Weighted mean tariff	-0.025	0.306
	(-0.23)	(0.89)
Control of corruption	-0.074	-1.478***
	(-0.52)	(-3.87)
Political stability	0.251***	0.094
	(2.96)	(0.41)
Regulatory quality	0.172	0.258
	(1.17)	(0.65)
Trade Partner FE	Yes	Yes
Year FE	Yes	Yes
Observations	830	725

Note: This table presents the determinants of LCT imports from China and LCT exports to China. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. t-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.2 The determinants of mineral trade with China

The results for the determinants of mineral trade are shown in Table 5. Different from the results for LCT trade, both mineral imports and exports tend to be strongly correlated with weighted mean tariff. An increasing weighted mean tariff would reduce both mineral imports from China and mineral exports to China. However, trade openness is found to have negative effect on mineral imports from China, partially due to the effect of trade diversification. Weak evidence has been documented that economically more developed countries tend to import more minerals from China and export less minerals to China. Finally, the uncertainty about exchange rate as indicated by rolling standard deviation would reduce mineral exports to China.

Table 5 Determinants of Mineral Trade with China

	Mineral imports from China (ln) (1)	Mineral exports to China (ln) (2)
GDP	0.420	2.100
	(0.23)	(1.02)
GDP growth	-0.127	-0.120
	(-0.63)	(-0.55)
GDP per capita	3.224*	-0.706
	(1.84)	(-0.36)
Gross domestic savings	-0.336	0.297
	(-0.88)	(0.76)
Domestic credit	-0.274	-0.096
	(-1.05)	(-0.27)
Inflation	18.891**	-10.693
	(2.23)	(-1.09)
Inflation (rolling SD)	0.317	1.192
	(0.37)	(1.37)
Real interest rate	0.212	-0.104
	(0.86)	(-0.40)
REER index (rolling SD)	0.215	-0.389**
	(1.35)	(-2.06)
Total reserves	0.211	-0.105
	(0.67)	(-0.25)
Trade openness	-0.813***	-0.346
	(-3.99)	(-1.34)
Population growth	0.095	-0.049
	(0.32)	(-0.18)
Weighted mean tariff	-0.942**	-0.837*
	(-2.13)	(-1.91)
Control of corruption	0.066	-0.056
	(0.13)	(-0.09)
Political stability	0.382	0.300
	(1.45)	(0.90)
Regulatory quality	-0.069	0.240
	(-0.14)	(0.39)
Trade Partner FE	Yes	Yes
Year FE	Yes	Yes
Observations	504	545

Note: This table presents the determinants of mineral imports from China and mineral exports to China. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. t-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.3 The environmental effects of LCT imports from China

The estimation results for the environmental impact of LCT trade with China are presented in Table 6.

Columns (1) – (4) report the estimated effects of LCT imports from China on the importer countries' CO2 emission. Specifically, the unit of CO2 emissions is log-transformed kt in column (1); tons per capita in column (2); kg per GDP in columns (3) and (4). We find that across all the CO2 measures, LCT imports from China is found to significantly reduce importer countries' CO2 emissions. Using more disaggregated level data, we further find that liquid fuel and fuel combustion in transportation sector are among the fuel categories that decrease the most. One explanation for the finding could be that the liquid fuel used in vehicles has been reduced due to the increasing imports of electronic vehicles or related technology from China. Finally, we recognize that such environmental effects of LCT imports haven't been documented for NO and PM2.5.

Table 6 Environmental Effects of LCT Imports from China

Dep: CO_2 emissions	All kt(ln) (1)	All tons/capita (2)	All kg/GDP(PPP) (3)	All kg/GDP(PPP,2017) (4)	Liquid Fuel kt(ln) (5)	Transportation % of fuel combustion (6)
LCT imports from China	-0.023***	-0.288***	-0.017***	-0.009***	-0.022***	-0.822***
	(-3.51)	(-9.63)	(-6.34)	(-7.05)	(-3.10)	(-5.46)
GDP growth	0.030***	0.049	0.017***	0.005**	0.035***	-0.404
	(3.07)	(1.10)	(4.24)	(2.45)	(2.82)	(-1.39)
GDP per capita	-0.321***	1.828***	-0.229***	-0.140***	-0.499***	-11.683***
	(-4.27)	(5.39)	(-7.45)	(-9.54)	(-4.62)	(-4.27)
Inflation	0.140***	0.173	0.091***	0.029***	0.064	-1.070
	(2.83)	(0.78)	(4.48)	(3.03)	(1.08)	(-1.06)
Trade openness	-0.071***	-0.242***	-0.052***	-0.023***	-0.056***	1.215***
	(-4.68)	(-3.52)	(-8.33)	(-7.82)	(-2.93)	(3.19)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Trade Partner FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,018	1,018	1,018	1,018	853	607

Note: This table presents the effects of importing LCT products from China on CO_2 emissions. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. t-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.4 Economic mechanisms

1.6.4.1 Human capital

Based on Equation (4), we are interested in whether human capital in the importer countries would affect the environmental effects of LCT imports from China. Thus, the interaction term between LCT imports and compulsory education as well as compulsory education itself are included in the regressions. As shown in Table 7, the interaction term between LCT imports and education tends to be negatively correlated with all the four aggregated measures of CO2 emissions. The results suggest that the environmental benefits of LCT imports from China are amplified by the education level in the importer countries, as human capital not only is linked to returns on R&D but also plays the key role in the adoption of foreign technology such as LCT.

Table 7 Mechanisms: Human Capital

Dep: CO2 emissions	All kt(ln) (1)	All tons/capita (2)	All kg/GDP(PPP) (3)	All kg/GDP(PPP,2017) (4)
LCT imports × Education	-0.021***	-0.312***	-0.006*	-0.004**
	(-2.99)	(-9.58)	(-1.92)	(-2.44)
LCT imports from China	-0.001	0.024	-0.008*	-0.004**
	(-0.07)	(0.58)	(-1.77)	(-2.26)
Compulsory education	0.038***	0.244***	0.019***	0.011***
	(3.65)	(5.07)	(3.94)	(5.18)
Control Variables	Yes	Yes	Yes	Yes
Trade Partner FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	825	825	825	825

Note: This table presents the joint effects of importing LCT products from China and human capital proxied by education on CO2 emissions. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. t-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.4.2 Political stability

The second potential mechanism is political stability. The effective use of low carbon technology imported from China can be dependent on the institutional environment of the importer countries. Countries with greater political stability are able to plan and achieve longer-term goals, especially those environment and technology related ones. Thus, we include the interaction term between LCT imports and political stability in the regressions. The results are presented in Table 8. The estimates for the interaction term are negative and statistically significant in columns (1), (2) and (4), indicating that LCT imports from China have larger effects on CO2 emissions in those countries with better political stability.

Table 8 Mechanisms: Political Stability

Dep: CO2 emissions	All kt(ln) (1)	All tons/capita (2)	All kg/GDP(PPP) (3)	All kg/GDP(PPP,2017) (4)
LCT imports × Political stability	-0.025**	-0.161***	-0.001	-0.004*
	(-2.16)	(-3.17)	(-0.27)	(-1.75)
LCT imports from China	-0.008	-0.192***	-0.013***	-0.006***
	(-0.88)	(-4.92)	(-3.81)	(-3.44)
Political stability	0.091***	0.145*	0.042***	0.022***
	(4.97)	(1.82)	(6.03)	(6.39)
Control Variables	Yes	Yes	Yes	Yes
Trade Partner FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	879	879	879	879

Note: This table presents the joint effects of importing LCT products from China and political stability on CO2 emissions. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. *t*-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.4.3 Foreign direct investment

FDI inflows is another variable that can potentially improve the adoption of LCT technology obtained from China. According to the previous research, FDI is usually associated with greater technology and human capital stocks, which are both important in the process of LCT adoption. Again, the interaction term between LCT imports and FDI inflows are included in the regressions. As shown in Table 9, the estimates for the interaction term are negative and statistically significant in columns (1) and (2). A certain amount of LCT imports from China can reduce more CO2 emissions given a larger amount of FDI inflows. However, no such effect is found for CO2 emissions per GDP.

Table 9 Mechanisms: Foreign Direct Investment

Dep: CO2 emissions	All kt(ln) (1)	All tons/capita (2)	All kg/GDP(PPP) (3)	All kg/GDP(PPP,2017) (4)
LCT imports × FDI inflows	-0.109**	-0.710***	0.005	-0.005
	(-2.37)	(-3.40)	(0.25)	(-0.57)
LCT imports from China	-0.034***	-0.352***	-0.017***	-0.010***
	(-4.36)	(-10.10)	(-5.35)	(-6.41)
FDI inflows	0.020	-0.018	0.012*	0.006*
	(1.25)	(-0.25)	(1.82)	(1.82)
Control Variables	Yes	Yes	Yes	Yes
Trade Partner FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,018	1,018	1,018	1,018

Note: This table presents the joint effects of importing LCT products from China and FDI inflows on CO2 emissions. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. *t*-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.4.4 Foreign aid

Development aid received from foreign countries is another factor that could facilitate the adoption of LCT technology. The majority of foreign aid is given by developed countries, which are usually with advanced technology and human capital. Such knowledge of technology and human capital could spillover to the foreign aid receipt countries. Thus, we include the interaction term between LCT imports and foreign aid received in the models. As shown in Table 10, the estimates for the interaction term are negative and statistically significant across columns (1) – (4). Accordingly, the environmental effects of importing LCT products from China are enhanced when the importer countries receive foreign aid.

Table 10 Mechanisms: Foreign Aid

Dep: CO2 emissions	All kt(ln) (1)	All tons/capita (2)	All kg/GDP(PPP) (3)	All kg/GDP(PPP,2017) (4)
LCT imports × Foreign aid received	-3.751***	-9.938***	-1.824***	-0.564**
	(-2.93)	(-3.14)	(-4.98)	(-2.42)
LCT imports from China	-1.107***	-2.785***	-0.555***	-0.167**
	(-2.92)	(-2.98)	(-5.11)	(-2.42)
Foreign aid received	-0.778***	-2.234***	-0.378***	-0.102**
	(-2.75)	(-3.20)	(-4.67)	(-1.98)
Control Variables	Yes	Yes	Yes	Yes
Trade Partner FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	625	625	625	625

Note: This table presents the joint effects of importing LCT products from China and foreign aid received on CO2 emissions. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. *t*-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.6.5 Gender analysis

As increased gender equality unlocks economic opportunities by broadening the talent pool and driving growth, particularly in low-carbon technologies and mineral trade, we next carry out a gender analysis based on the empirical framework to examine the nexus of gender equality and LCT trade. Specifically, we include additional gender-related variables in Equations (1) and (2) to examine whether trade in LCTs and minerals is relevant to female performance in the workplace. It is important to note that the previously identified determinants of LCT and mineral trade are included as control variables, whose estimates are not reported for simplicity. The results for LCT trade are presented in Table 11, and those for mineral trade are in Table 12.

In particular, we find that gender equality is highly correlated with countries' LCT exports to China. For instance, the ratio of female employer to total female employment, the employment rate of females and the ratio of female employment in services are all positively correlated with LCT exports to China, which suggests that the presence of female in the workplace and especially in positions of leadership is one of the most important drivers of exporting LCTs. In contrast, LCT imports from China tend to be less correlated with the gender-specific performance in importing countries, except that the ratio of female employment in industry tends to be negatively associated with LCT imports from China.

Models in Table 12 shows that both mineral imports from China and exports to China are significantly correlated with the performance of gender variables. Specifically, the ratio of female employer to total female employment and the ratio of female to male labor force participation both positively contribute to mineral imports from China. That being said, the relative performance of females in sociey is one of the determinants of mineral imports from China. In addition, the ratios of female employment in industry and services and the general labor force participation of female are all positively correlated with mineral exports to China. In other words, the presence of female in industry and the services sectors is particularly crucial to the exports of minerals and thus to the aggregated economy.

In summary, our gender analysis provides evidence for the importance of female performance to international trade in LCTs and minerals. This likely suggests that female participation and the environment of inclusion in a society contribute the competitiveness of the economy. Therefore, the economic and environmental opportunies offered by sustainable trade and sustainable supply chains can be better seized in a country with better inclusion of women in the labor force.

Table 11 Gender-related Determinants of LCT Trade with China

	LCT imports from China (ln)	LCT exports to China (ln)
	(1)	(2)
Female employer	0.054	0.366**
	(0.87)	(2.20)
Female employment	0.257	2.195**
	(0.63)	(2.02)
Female employment in industry	-0.281*	0.177
	(-1.96)	(0.45)
Female employment in services	0.254	2.426***
	(0.79)	(2.84)
Female labor force participation	0.060	-1.261
	(0.11)	(-0.89)
Female to male labor force participation	-0.342	-0.436
	(-1.03)	(-0.51)
Control Variables	Yes	Yes
Trade Partner FE	Yes	Yes
Year FE	Yes	Yes
Observations	802	707

Note: This table presents the gender-related determinants of LCT imports from China and LCT exports to China. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. t-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 12 Gender-related Determinants of Mineral Trade with China

	Mineral imports from China (ln)	Mineral exports to China (ln)
	(1)	(2)
Female employer	0.494**	-0.224
	(2.32)	(-0.86)
Female employment	-1.223	-3.342*
	(-0.82)	(-1.94)
Female employment in industry	-1.094*	1.800***
	(-1.87)	(3.01)
Female employment in services	-0.154	4.240***
	(-0.12)	(3.01)
Female labor force participation	-0.521	3.895*
	(-0.27)	(1.70)
Female to male labor force participation	3.134***	-1.984
	(2.83)	(-1.40)
Control Variables	Yes	Yes
Trade Partner FE	Yes	Yes
Year FE	Yes	Yes
Observations	504	545

Note: This table presents the gender-related determinants of mineral imports from China and mineral exports to China. All the independent variables are standardized and one-period lagged. Trade partner and year fixed effects are included in each specification. *t*-statistics are reported in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

1.7 Policy Recommendations

1.7.1 Boost R&D subsidies for renewable energy to innovate and lead globally in energy security

China should maintain and potentially increase R&D subsidies for renewable energy technologies. This support should not be limited to promoting exports but also focus on enhancing domestic utilization and adoption of renewable energy solutions. By fostering innovation and technological advancements within the country, China can strengthen its position as a global leader in renewable energy while simultaneously addressing domestic energy needs and environmental challenges. Sustained R&D subsidies will drive innovation, making Chinese renewable energy technologies more competitive globally, reduce reliance on fossil fuels, lower carbon emissions, and improve energy security. Specifically, China can create a dedicated national fund to finance research and development projects in renewable energy, offer tax incentives to companies and research institutions that invest in renewable energy R&D, develop regional innovation hubs focused on renewable energy R&D to drive regional economic growth and specialization, and strengthen cooperation with Global South on policy banks and R&D in general.

First, establish national renewable energy R&D fund: Allocate a substantial annual budget to the fund, sourced from government revenues, international grants, and private sector contributions. Implement competitive grant programs to support innovative projects in solar, wind, biomass, and other renewable energy technologies. Encourage collaborations between universities, research institutions, and private companies to foster innovation and technology transfer. Establish a robust monitoring and evaluation framework to ensure transparency and effectiveness of the fund’s expenditures and to measure the impact of funded projects.

Second, provide tax incentives for renewable energy R&D: Introduce tax credits equivalent to a percentage of the R&D expenses incurred by companies working on renewable energy technologies. Allow accelerated depreciation on capital expenditures related to renewable energy R&D equipment and facilities. Offer additional tax deductions for the salaries of scientists, engineers, and other personnel directly involved in renewable energy R&D. Provide tax reductions or exemptions for income derived from patents and intellectual property generated through renewable energy R&D activities.

Third, construct regional renewable energy innovation hubs: Invest in state-of-the-art research facilities and laboratories in key regions with high renewable energy potential. Provide seed funding, mentorship programs, and business incubation services to renewable energy startups located in these hubs. Facilitate partnerships between local governments, academic institutions, and private enterprises to jointly undertake large-scale R&D projects. Implement programs to attract and retain top domestic and international talent in the field of renewable energy through grants, scholarships, and attractive living conditions in innovation hubs.

Fourth, establish partnerships between China's policy banks and their counterparts in the Global South: Establish renewable energy project pipeline facilities and other partnerships that could lower the cost of capital for renewable energy and the transaction costs of technology transfer from China to Global South. Strengthen the cooperation of R&D between China and the Global South in general. The partnerships should pay particular attention to the trade partners that mainly export transition minerals. The partnerships can help trade partners reduce carbon emission through producing minerals and move up the value chain on transition minerals.

1.7.2 Stabilize export prices to foster steady trade and investment relationships with partners

China should implement policies to maintain stable export prices, particularly with its major trading partners on low-carbon technology products and related minerals. Stable exports prices can reduce uncertainty for exporters, importers and investors, promoting steady trade and investment relationships. Specifically, China can monitor export prices for predictions and warnings, expand and enhance bilateral currency SWAP agreements with key trading partners, engage in regular macroeconomic policy coordination with key trading partners to promote export price stability.

First, establish a comprehensive system to monitor export prices closely, especially in key sectors such as low-carbon technology and related minerals: By tracking price trends, market demand, and global economic factors, China can identify early warning signs of price volatility and respond proactively. This monitoring system could include data analytics tools to predict potential price fluctuations, allowing exporters to adjust strategies in advance. Regular communication of these predictions and warnings to stakeholders would help mitigate risks and stabilize export prices over the long term.

Second, strengthen bilateral currency SWAP agreements: Negotiate and establish bilateral currency SWAP agreements with major trading partners to facilitate trade and investment without relying on third-party currencies. Set clear terms and conditions for currency SWAPs, including SWAP amounts, duration, and interest rates, to ensure mutual benefits and stability. Use currency SWAPs to provide liquidity support during periods of financial stress, reducing the risk of price volatility. Monitor and periodically review the effectiveness of currency SWAP agreements, making adjustments as necessary to optimize their impact on export price stability.

Third, coordinate macroeconomic policies with key trading partners: Establish formal mechanisms for regular dialogue and coordination on macroeconomic policies with major trading partners, focusing on monetary, fiscal, and trade policies. Align interest rate policies and inflation targets to reduce discrepancies that could lead to export price fluctuations. Collaborate on economic forecasts and policy responses to global economic developments to ensure synchronized and mutually supportive economic strategies. Foster transparency and data sharing between countries to build trust and facilitate informed decision-making in export price management.

1.7.3 Encourage outward FDI in renewable energy and low carbon technologies to promote global cooperation

China should continue to encourage and facilitate outward FDI on renewable energy and low carbon technologies to destination countries, especially those major trading partners. Outward FDI helps integrate China more deeply into the global economy, fostering stronger economic ties and collaboration. Firms can gain access to new markets, resources, and technologies, enhancing their productivity and competitiveness. Outward FDI can also diversify income sources and reduce economic vulnerability to domestic market fluctuations, especially for the renewable energy sector. Specifically, China can establish comprehensive financial incentives and support mechanisms to encourage Chinese enterprises to invest in renewable energy and low carbon technology sectors abroad, foster bilateral and multilateral partnerships to facilitate technology transfer and improve market access for Chinese renewable energy and low carbon technology firms, and pay particular attention to South-South cooperation.

First, provide financial incentives and support for outward FDI in renewable energy and low carbon technology: Implement tax breaks, low-interest loans, and grants for companies investing in renewable energy and low carbon technologies in foreign markets. Create dedicated funds or financing institutions to provide capital for overseas investments in these sectors. Offer risk mitigation tools such as insurance and guarantees to protect against political and economic risks in host countries. Additionally, streamline administrative processes and reduce bureaucratic hurdles for outward FDI, making it easier for companies to navigate regulatory environments.

Second, develop bilateral and multilateral partnerships for technology transfer and market access: Negotiate and establish agreements with host countries that promote technology exchange, joint ventures, and collaborative research and development in renewable energy and low carbon sectors. Engage in diplomatic efforts to create favorable regulatory environments for Chinese investments, including removing trade barriers and ensuring fair competition. Work with international organizations and development banks to co-finance and support large-scale renewable energy projects that involve Chinese companies. Promote China's renewable energy and low carbon technologies at international trade fairs and forums to attract potential partners and investors.

Third, strengthen South-South cooperation: China should actively pursue and strengthen South-South cooperation by establishing joint ventures and FDI partnerships with countries in the Global South. These initiatives should focus on promoting the transfer of renewable energy and low carbon technologies, facilitating the extraction and processing of transition minerals, and building local capacity through comprehensive technology transfer and training programs. By doing so, China can ensure that developing countries co-benefit from technological advancements and move up the value chain, leading to sustainable economic growth and reduced carbon emissions. Strengthening South-South cooperation will not only support the development of partner countries but also enhance China's leadership in global green technology initiatives. A good example would be China’s EV investment in Hungary over the last years.

1.7.4 Advance trade liberalization to foster sustainable trade practices and interconnected supply chains globally

China should pursue further trade liberalization for the development of sustainable trade and supply chains. Further trade liberalization can create more business opportunities for domestic firms in renewable energy sector and increase their productivity and competitiveness. Specifically, China can proceed diversification of export destinations, expansion of import scale, specialization of service trade, multi-layered regional economic cooperation and differentiation of the Belt and Road Initiative.

First, diversification of export destinations: Given the current complex and ever-changing international situation, Chinese export companies should not only target mature markets in Europe and the United States but also actively explore emerging markets such as BRICS countries and Central Asia. When exporting products to different countries, Chinese companies should provide differentiated products based on the income levels and real situations of the destination to better meet local demands while enhancing competitiveness.

Second, expansion of import scale: From a macro policy perspective, imports should be continuously expanded, tariffs reduced, and trade costs minimized. This would allow more products to enter the domestic market, enhancing consumer satisfaction and sense of gain. From a business perspective, if imported goods are intermediate products, cost reductions will benefit sustainable profit growth and local fiscal revenue. If imported goods are final products, reduced tariffs might bring short-term competition, but in the long run, increased industry productivity will benefit industry development.

Third, specialization of service trade: China is already the largest goods trading nation globally, but there is still significant room for growth in service trade. Efforts should be made to expand the total volume, adjust the structure, and establish unique features. According to the recently released "China Service Trade Development Report 2022," the total volume of China's service trade reached $889.1 billion, which is still behind the total volume of the United States. Structurally, China has a large deficit in key industries, such as education services, one of the largest deficit industries. Measures should be taken to expand the service trade surplus. As China opens its doors, its rich tourism resources should attract more foreign tourists, but soft infrastructure needs improvement to enhance travel service quality. China should identify comparative advantages in its service trade industries to establish unique features, such as the traditional Chinese medicine industry. Clean energy services that involve the integration of renewable energy solutions with products to enhance sustainability and reduce carbon footprint could be another source of growth.

Fourth, multi-layered regional economic and trade cooperation: China is currently advancing its process to join the CPTPP, but due to the many member countries and relative complexity, achieving this in the short term is challenging. It is also crucial to promote the China-Japan-Korea Free Trade Area from factor openness to institutional openness. The geographic proximity and complementary advantages of China, Japan, and Korea mean that expanding economic and trade cooperation among these three countries will help promote regional economic integration and strengthen regional industrial chain cooperation.

Fifth, differentiation of the Belt and Road Initiative: As the Belt and Road Initiative enters its next decade, the focus for the future should be on strengthening economic and trade cooperation with Russia's Far East on the land-based Silk Road. The maritime Silk Road should adopt a "dual-track" approach: promoting the China-Japan-Korea Free Trade Area to the north and enhancing economic and trade cooperation with the Middle East, West Asia, and North Africa to the south, particularly advancing free trade agreements with Iran, Saudi Arabia, and Egypt. By developing the land-based Silk Road to the east and the maritime Silk Road to the north, a large Northeast sea-land corridor can be established, reshaping China's strategic landscape for external openness.

1.7.5 Improve external communication to eliminate misunderstandings about China's overcapacity

China's overcapacity is often misinterpreted, particularly in international contexts where it is wrongly linked to product dumping in developed countries like the United States. To effectively counter these misconceptions, China should enhance its external communication strategies. This includes ensuring consistency in messaging between domestic and international platforms, and articulating China's position clearly and confidently in global forums. Specifically, China should focus on the concept of overcapacity, the causes of overcapacity, the interpretation of industrial policy and the fallacies in the U.S. anti-dumping measures.

First, it is crucial to grasp the concept of overcapacity. Whether China experiences overcapacity depends on how it is measured. If overcapacity is defined as the difference between potential production and actual production, then China indeed shows some signs of overcapacity to a certain extent. However, there is a fundamental difference between the overcapacity China refers to and the overcapacity-induced dumping claimed by the United States. From this perspective, overcapacity is a misleading concept.

Second, the causes of overcapacity need to be analyzed. Overcapacity is a common issue in global economic development. According to our calculations, China's capacity utilization rate, similar to that of the European Union, the United States, and Brazil, falls within a reasonable range of overcapacity. Since this is a common issue, the root causes of overcapacity need further exploration. The causes of overcapacity can be attributed to four main factors:

1. **Market Factors**: This mainly manifests as insufficient effective demand, with the current overcapacity primarily stemming from weakened demand following the 2008 global financial crisis.
2. **Corporate Factors**: The rush towards new industries, leading to phenomena such as "herd behavior."
3. **Industry Factors**: Certain industries have not deeply explored new productive capacities, with investment methods remaining crude and entry barriers low.
4. **Local Government Factors**: Fiscal investment has become a significant driving force behind overcapacity.

Among these factors, insufficient effective demand is the primary cause of overcapacity. The root cause of China's current overcapacity lies mainly in the global market's insufficient effective demand. To address this issue, China should actively work to build a unified national market, aiming to alleviate the pressure caused by insufficient global demand.

Third, China's industrial subsidy policy needs to be correctly interpreted. There is a logical error in the assertion that "industrial subsidies lead to overcapacity, which then leads to product dumping." When evaluating whether industrial subsidies impact exports, the standard should be whether China's subsidy policies violate the relevant rules established by the WTO. Currently, China's industrial subsidies are primarily focused on R&D to promote technological innovation, and do not violate the WTO's red subsidy provisions. Furthermore, the beneficiaries of these subsidies include a variety of ownership structures, such as state-owned enterprises, private enterprises, and foreign-funded enterprises.

Fourth, the fallacies in the U.S. anti-dumping measures against China should be clarified.

1. **Insufficient Evidence**: Chinese imports of automobiles have not caused substantial harm to the U.S. domestic automotive industry. China's exports of new energy vehicles to the U.S. account for only 1% of total U.S. auto sales, which is insufficient to cause significant damage to the U.S. domestic auto

industry. In reality, the challenges faced by the U.S. automotive industry primarily stem from its own industrial hollowing-out and incomplete value chains, rather than competition from Chinese imports.

2. **Excessive Severity**: The average U.S. tariff rate is around 37%, and China is designated as a non-market economy, subject to anti-dumping duties as high as 100% on new energy vehicles. This approach is evidently unreasonable. The establishment of a socialist market economy is a great achievement of socialism with Chinese characteristics. While China's economy does experience some imbalances and underdevelopment, it is undoubtedly a market economy, with the market playing a decisive role in resource allocation.

1.8 Conclusion

The global trade of LCTs and related minerals has undergone significant transformations over the past three decades, driven largely by policy initiatives, technological advancements, and the strategic roles played by key nations, particularly China. This research has provided a comprehensive analysis of sustainable trade and supply chains, emphasizing the critical role of LCTs in mitigating climate change and promoting sustainable development. By examining the dynamics of LCT trade, its environmental impacts, and the factors influencing these trends, this study offers valuable insights into the complex interplay between trade policies, technology and industrial development, and climate sustainability.

The report provides a comprehensive understanding of the current state of sustainable trade and supply chains, the environmental benefits, and the necessary steps to enhance its effectiveness. Using a novel dataset on bilateral LCT trade, we find China has become a net-exporter since the late 2000s. Countries' economic development and trade openness are the key factors contributing to this trend. Greater gender equality can improve countries' competitiveness in the global clean technology market. More importantly, the adoption of LCTs through international trade is associated with the reduction of carbon emissions.

The findings indicate that China can lead in sustainable trade through international cooperation. To encourage a sustainable global LCT trade and fast energy transition, this report suggests that the Chinese government should enhance its srategic investments in renewable energy, maintain stable export price, facilitate outward foreign direct investment in renewable energy sectors, pursue responsible trade and investment that incorporate environmental and social protection in the Global South, and improve external communication about overcapacity. These measures are essential for bolstering economic growth and contributing to global sustainability. Furthermore, strengthening South-South cooperation through joint ventures and FDI partnerships will facilitate technology transfer, capacity building, and economic advancement for developing countries. By leveraging its expertise and resources, China can assist partner nations in moving up the value chain and achieving sustainable growth, thereby creating a more equitable and environmentally sustainable global economy.

The report calls for a concerted effort from policymakers, businesses, and international organizations to work towards a sustainable future. By aligning economic activities with environmental goals, it is possible to create resilient and sustainable trade networks that benefit both the economy and the planet.

While this report provides a comprehensive analysis of the global LCT trade and China's role in it, it is crucial to deepen our understanding of the entire supply chain of the global LCT industry. Specifically, the global trade of transition minerals is another critical issue that warrants systematic investigation. Driven by the burgeoning global LCT market, there has been a significant increase in demand for transition materials such as lithium, cobalt, and nickel. The escalating demand has underscored potential risks, including highly concentrated supply and severe environmental and social impacts within the transition material industrial chain. Therefore, the trade relationships between China and mineral-exporting countries, China's FDI in the mining sector, as well as social-ecological and geopolitical risks associate with them, are of particular importance. Moreover, intensifying geopolitical competitions have posed significant threats to the stability of the supply chain, which in turn impacts the stability of the global LCT market. In the next SPS report, we will conduct a thorough investigation of the state of transition mineral supply chain based on the current study.

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